Overview of Hybrid Power System

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Abstract Hybrid power system (HPS) is an electricity generation system combining renewable energy resources and conventional generators. Several components will be utilized in a hybrid power system namely as: conventional generators (diesel generator, synchronous generator, DC generator for field excitation of synchronous generator), renewable energy resources (such as wind generator, photovoltaic system, etc.), power electronic converter, components' controller, and also a supervisory control system to control the whole power system. In this chapter, an overview of hybrid power system and a brief description of important possible parts of a hybrid power system is introduce.

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1 Introduction

Conventional generation systems such as thermal and nuclear power system are not a proper solution to electrification of remote areas due to economical and technical issues. Beside environmental problems such as emissions and greenhouse gas effects which are caused by conventional generation systems, the high cost of fuel, and construction of these power plants as well as efficiency and reliability are also serious problems of conventional generation systems. Hybrid power systems are an alternative solution to supply remote loads.

Hybrid power systems utilize both conventional and renewable resources to supply demand. As regards this demand is usually at remote point; hence, the local renewable resources should be utilized. Diesel generators as a conventional generation system, wind turbine, photovoltaic cell, fuel cell, and its relevant components, and other renewable-based generation system may be used in a hybrid power system.

Moreover, the integration of renewable energy resources into conventional system can bring reliability and efficiency to supply demand and the cost of components is expected to decline. However, further improvement in design and operation of hybrid power system is still needed.

On the contrary, the most important problem of hybrid power systems is the complicated control system. Although each component has their own control system, a controller should supervise the actions of each individual controller. The action of supervising controller is called supervisory control and this system is called supervisory control system. This system receives the operation status of each component and sends a signal to set the reference point of each component.

In this chapter, at first, the main power plants in large capacity scale are briefly introduced and described. After that generators as the main component of any generation system are introduced in which both AC and DC generators are described briefly. Power transformers are also included in this section. The chapter continues with renewable energy resources and their relevant power plants followed by supervisory control system of a hybrid power system and its management issues.

2 Main Power Plants

Electric power is generally generated using conventional generators based on nonrenewable energy sources such as coal, oil, natural gas, and Uranium. The capacity of these generators is very high, since they are responsible for producing bulk amounts of power necessary to supply the entire loads. However, supply of fuels for these generation technologies is limited and creates the need for looking at alternative renewable fuel sources.

The main component to generate electric power is generator. When a generator is coupled with a prime mover, the electricity is generated. However, the type of power plant is determined by the type of prime move.

2.1 Steam Power Plants

Steam is an important medium to produce mechanical energy. The most important merits of steam is that it can be raised from water which is available in abundance, it does not react much with the materials of power plant equipments, and it is stable at the temperature required in the plant. Steam is used to drive steam engines, steam turbines, etc. A steam power plant must have a furnace to burn the fuel, steam generator, or boiler containing water, main power unit such as an engine or turbine to use the heat energy of steam and perform work, and piping system to convey steam and water.

In addition, the plant requires various auxiliaries and accessories depending on the availability of water, fuel and the service for which the plant is intended.

A steam power plant using steam as working fluid works basically on Rankine cycle. Steam is generated in a boiler, expanded in the prime mover, and condensed in the condenser and fed into the boiler again. The different types of systems and components used in steam power plant are high pressure boiler, prime mover, condensers and cooling towers, coal handling system, ash and dust handling system, draft system, fed water purification plant, pumping system, air preheater, economizer, super-heater, and feed heaters.

The heat produced by burning of coal converts water stored in boiler into steam at suitable pressure and temperature. The generated steam is passed through the super-heater. The superheated steam then flows through the turbine; and consequently the pressure of steam is reduced due to work which is done in the turbine. Steam which leaves the turbine passes through the condenser whose steam pressure depends on flow rate and temperature of cooling water and effectiveness of air removal equipment. Water circulated through the condenser may be taken from the various sources such as river, lake, or sea. If sufficient water is not available, the hot water coming out of the condenser may be cooled in cooling towers and circulated again through the system. Air taken from the atmosphere is first passed through the air preheater, where it is heated by flue gases. The hot air then passes through the furnace. The flue gases passes over boiler and super-heater pipes, after that they flow through the filter and then economizer, and finally they are exhausted to the atmosphere through the chimney.

2.2 Gas Turbine Power Plant

A simple cycle of a gas turbine power plant consists of a compressor, a combustion chamber, and a turbine. The gas turbine obtains its power by utilizing the energy of burnt gases and air whose pressures are high in the range of 4–10 bars. This high pressure produced by compressor which can be centrifugal or axial. Moreover, the compressor is driven by turbine.

To get a higher temperature of the working fluid, a combustion chamber is required where combustion of air and fuel takes place. Beside temperature and pressure, the volume of working fluid is another important parameter. Increasing the volume of the working fluid at constant pressure, or alternatively increasing the pressure at constant volume can increase the power developed by the turbine.

Regarding the fact that the compressor is coupled with the turbine shaft, it consumes some of the power produced by the turbine; hence, the compressor lowers the efficiency. Therefore, the network is the difference between the turbine work and work consumed by the compressor.

The gas turbine power plants which are used in electric power industry are classified into two groups: open cycle gas turbine and closed cycle gas turbine.

2.2.1 Open Cycle Gas Turbine

As is shown by Fig. 1 a simple open cycle gas turbine consists of a compressor, combustion chamber, and a turbine. The compressor takes in ambient air and raises its pressure. Heat is added to the air in combustion chamber by burning the fuel and raises its temperature. The compressor takes in ambient air and raises its pressure. Heat is added to the air in combustion chamber by burning the fuel and

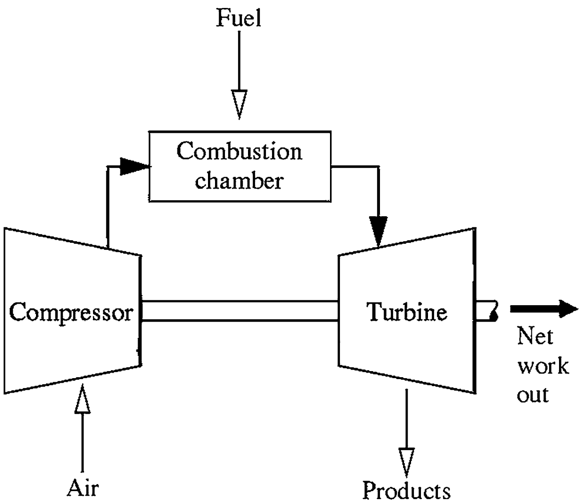


Fig. 1 The schematic diagram of an open cycle gas turbine power plant [2]

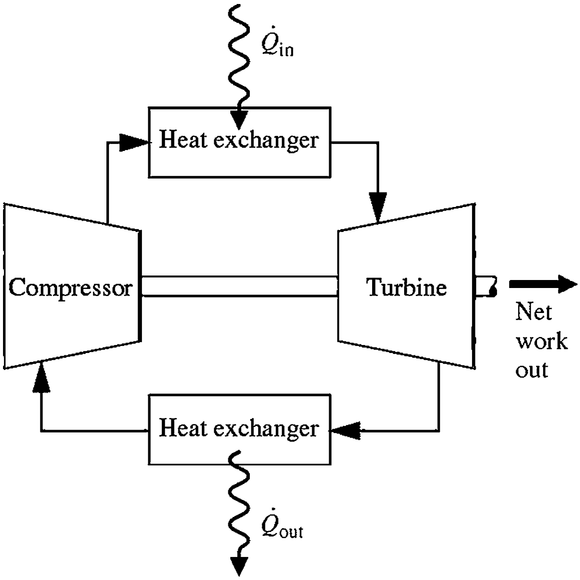


Fig. 2 The schematic diagram of a closed-loop gas turbine power plant [2]

raises its temperature. The hot and high pressure gas then flows to turbine, after that the exhausted steam returns back to atmosphere [1].

2.2.2 Closed Cycle Gas Turbine

As is illustrated in Fig. 2, in closed cycle gas turbine plant, the working fluid (air or any other suitable gas) which comes out from compressor is heated in a heater by an external source at constant pressure. Then, the high temperature and high pressure air results from the external heater is passed through the gas turbine. After that, the gas coming out from the turbine is cooled to its original temperature in the cooler using external cooling source before passing to the compressor. Therefore, the working fluid is continuously used in the system without its change of phase and the required heat is given to the working fluid in the heat exchanger [1].

2.3 Combined Cycle Power Plants

As is described previously, significant amount of thermal energy is wasted at steam output of turbine both in open cycle and closed cycle technologies. If this energy can be utilized, the efficiency of power plans will be enhanced. Generally, the thermal energy of exhausted steam from gas turbine is used to preheat the working fluid of a steam turbine in a combined cycle power plant. There may be

various combinations of the combined cycles depending upon the place or country requirements. Even nuclear power plant may be used in the combined cycles.

In a combined cycle power plant, the exhaust of gas turbine which has high oxygen content is used as the inlet gas to the steam generator where the combustion of additional fuel takes place. This combination allows nearer equality between the power outputs of the two units than is obtained with the simple recuperative heat exchanger. For a given total power output, the energy input is reduced (i.e., saving in fuel) and the installed cost of gas turbine per unit of power output is about one-fourth of that of steam turbine. In other words, the combination cycles reveal higher efficiency. The greater disadvantages include the complexity of the plant, different fuel requirements, and possible loss of flexibility and reliability [1].

2.4 Nuclear Power Plants

Nuclear energy is an important source for electricity generation in many countries. In 2003, 19 countries depended on nuclear power for at least 20 % of their electricity generation. France is the country which has the highest portion (78.1 %) of the electricity generated by nuclear power. Though the percentage of nuclear electric power over the total national electricity generation is not very high (about 20 %), the U.S. is still the world's largest producer of electric power using nuclear fuels. Higher fossil fuel prices and the entry into force of the Kyoto Protocol could result in more electricity generated by nuclear power. In the emerging economic regions, such as China and India, nuclear power capacity is expected to grow. However, nuclear power trends can be difficult or even be reversed due to a variety of reasons. The safety of a nuclear power plant is still the biggest concern. And how to deposit nuclear wastes can always be a discussion topic for environmentalists. Moreover, the nuclear fuel (Uranium) is not renewable [2].

The main advantages and disadvantages of nuclear power plants are:

- Space requirement of a nuclear power plant is less as compared to other conventional power plants of equal size.
- A nuclear power plant consumes very small quantity of fuel. Thus fuel transportation cost is less and large fuel storage facilities are not needed Further, the nuclear power plants will conserve the fossil fuels (coal, oil, gas, etc.) for other energy need.
- There is increased reliability of operation.
- Nuclear power plants are not affected by adverse weather conditions.
- Nuclear power plants are well suited to meet large power demands. They give better performance at higher load factors (80–90 %).
- Materials expenditure on metal structures, piping, storage mechanisms are much lower for a nuclear power plant than a coal burning power plant.
- It does not require large quantity of water.

- Initial cost of nuclear power plant is higher as compared to hydro or steam power plant.
- Nuclear power plants are not well suited for varying load conditions.
- Radioactive wastes if not disposed carefully may have bad effect on the health of workers and other population.
- Maintenance cost of the plant is high.
- It requires trained personnel to handle nuclear power plants.

2.5 Hydroelectric Power Plant

Today, hydropower is still the largest renewable source for electricity generation in the world. In 2002, more than 18 % of the world electricity was supplied by renewable sources, most of which comes from hydropower. The world hydroelectric capacity is expected to grow slightly due to large hydroelectric projects in the regions with emerging economies.

Although the hydropower is clean and renewable, there are still some problems associated with it. First, the big dams and reservoirs cause a lot of environmental concerns and social disputes. Second, the repositioning of reservoir populations can be a big crisis. Moreover, hydropower is not as profuse as desired.

If at a certain point, the water falls through an appreciable vertical height, this energy can be converted into shaft work. As the water falls through a certain height, its potential energy is converted into kinetic energy and this kinetic energy is converted to the mechanical energy by allowing the water to flow through the hydraulic turbine runner. This mechanical energy is utilized to run an electric generator which is coupled to the turbine shaft.

Some Hydroelectric Power plants are located on rivers, streams, and canals, but for a reliable water supply, dams are needed. Dams store water for later release for such purposes as irrigation, domestic and industrial use, and power generation. The reservoir acts much like a battery, storing water to be released as needed to generate power.

3 Generators

3.1 AC Generators

AC generators are synchronous machines capable of generating AC electric power. The interactions between the multipole magnetic fields of the stators (armatures) and rotors of synchronous generators generate the electrical power. The interaction is called *synchronous* because when the generator is running, the stator and rotor magnetic fields turn at the same speed. A single small generator might have a rating of a few hundred watts, but the largest single machines have ratings that

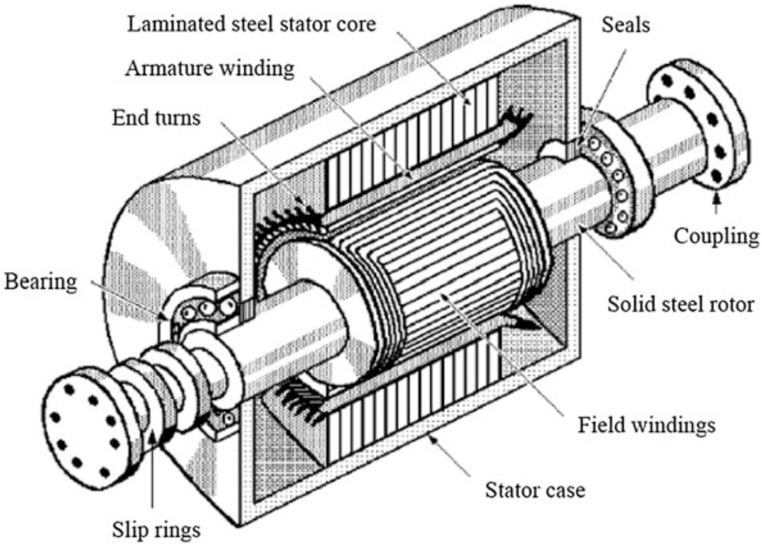


Fig. 3 A cutaway view of a synchronous generator [3]

exceed a billion watts. All synchronous generators have wound armatures and rotors, but the armature is wound on the stator rather than on the rotor, and the field winding is wound on the rotor. Figure 3 illustrates a cutaway view of a synchronous AC generator with a solid cylindrical wound rotor that permits it to turn at high speed without self-destructing.

The organization of a utility AC generator is opposite that of most DC generators and both AC and DC motors. If these machines have armatures, they are wound on their rotors; if they have field windings, they are wound on their stators. The construction of AC generators is reversed to eliminate the complexities of slip-ring mechanisms for obtaining the AC power and to provide more stable mechanical support for the stator windings. With more rigid support, the stators eliminate vibrations that create centrifugal forces which degrade the quality of the AC output. The armature windings are fitted tightly into slots on the inner surface of the stator formed by stacking magnetic sheet steel laminations. The field coils are then wound in axial slots in the outer surface of the solid cylindrical magnetic steel rotor. The rotor and stator together form the magnetic circuit. Most utility AC generators have a three-phase armature winding [3].

The insulation of the AC generator is simplified by having a revolving field and stationary armature. As the poles move under the armature conductors on the stator, the field flux cutting across the conductors induces an alternating voltage. It is alternating because poles of opposite polarity pass successively by a given stator conductor. The alternating voltage appears at the stator windings and is brought out directly through insulated leads from the stationary armature.

Because the most utility of AC generators run at constant speed, the voltage generated depends on field excitation. The rotating field is supplied with 120 or 240 V DC from a separate small DC generator called an *exciter* through two slip rings and brushes. This arrangement permits the generated voltage to be controlled by adjusting the amount of field excitation supplied to the exciter. The field excitation, in turn, is controlled by varying the excitation voltage applied to the alternator field.

Synchronous AC generators are fitted with one of two different rotor designs depending on their intended rotational speeds.

Round rotors are solid steel cylinders with the field winding inserted in slots milled into the surface or the rotor. They usually have two or four poles. Round rotors can withstand the stresses of high-speed rotation.

Salient-pole rotors have multiple pole pieces (typically six) mounted to the rotor structure, and the field winding is wound around the pole pieces. Because of their more complex construction and larger diameter-to-length ratios, salient-pole rotors cannot withstand the stresses of high-speed rotation.

Electric utility steam turbine-driven generators designed for 50- or 60-Hz AC output voltage have round rotors with two poles because they can withstand the stresses of speeds of 3000 and 3600 rpm. Hydroelectric, diesel, and natural-gas engines have far lower shaft speeds than steam turbines, so the generators they drive usually have six or more pole rotors, requirements usually met with more complex salient-pole rotors.

Three-phase AC generators have a winding that is made up of three separate stator windings, each displaced from the other two by 120 electrical degrees. The three windings can either be *wye* or *delta* connected. The wye connection is more common because it is better suited for direct high-voltage generation.

3.2 DC Generator

Although a far greater percentage of the electrical machines in service are A.C machines, the D.C machines are of considerable industrial importance. The main advantage of the D.C machine, specially the D.C motor, is that it provides a fine control of speed. Such an advantage is not claimed by any A.C motor. However, D.C generators are not as common as they used to be, because direct current, when required, is mainly obtained from an A.C supply by the use of rectifiers. Nevertheless, an understanding of D.C generator is important because it represents a logical introduction to the behavior of D.C motors. Indeed many D.C motors in industry actually operate as D.C generators for a brief period [4].

The D.C generators and D.C motors have the same general construction. On the other word, when the machine is being assembled, the workmen usually do not know whether it is a D.C generator or motor. Any D.C generator can be run as a

D.C motor and vice versa. All D.C machines have five main components namely, field system, armature core, armature winding, commutator, brushes.

The function of the field system is to produce uniform magnetic field in which the armature rotates. Field system consists of a number of salient poles (of course, even number) bolted to the inside of circular frame (generally called yoke). Whereas, the pole pieces are composed of stacked laminations the yoke is usually made of solid cast steel.

The armature core is keyed to the machine shaft and rotates between the field poles. It consists of slotted soft-iron laminations (about 0.4 to 0.6 mm thick) that are stacked to form a cylindrical. The laminations are separately encrusted with a thin insulating film so that they do not come in electrical contact with each other. The laminations are slotted to provide accommodation and provide mechanical security to the armature winding and to give shorter air gap for the flux to cross between the pole face and the armature "teeth".

The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding. This is the winding in which "working" E.M.F. is induced. The armature conductors are connected in series–parallel; the conductors being connected in series so as to amplify the voltage and in parallel paths so as to increase the current. The armature winding of a D.C. machine is a closed-circuit winding; the conductors being connected in a symmetrical manner forming a closed loop or series of closed loops.

A mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes is commutator. It is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine. The armature conductors are soldered to the commutator segments in a suitable manner to give rise to the armature winding. Depending upon the manner in which the armature conductors are connected to the commutator segments, there are two types of armature winding in a D.C. machine: lap winding and wave winding.

Great care is taken in building the commutator because any eccentricity will cause the brushes to bounce, producing unacceptable sparking. The sparks may bum the brushes and overheat and carbonize the commutator.

The principle of brushes is to guarantee electrical connections between the rotating commutator and stationary external load circuit. The brushes are made of carbon and rest on the commutator. The brush pressure is adjusted by means of adjustable springs. If the brush pressure is very large, the friction produces heating of the commutator and the brushes. On the other hand, the not good enough contact with the commutator may produce sparking if it is too weak.

Multipole machines have as many brushes as they have poles. For example, a 4-pole machine has 4 brushes. As we go round the commutator, the successive brushes have positive and negative polarities. Brushes having the same polarity are connected together.

3.3 Diesel Engines

The oil engines and gas engines are called Internal Combustion (IC) Engines. In IC engines, fuels burn inside the engine and the products of combustion form the working fluid that generates mechanical power. Whereas, in Gas Turbines the combustion occurs in another chamber and hot working fluid containing thermal energy is admitted in turbine. Reciprocating oil engines and gas engines are of the same family and have a strong resemblance in principle of operation and construction. The engines convert chemical energy in fuel into mechanical energy.

A typical oil engine has the following components [3]:

- Cylinder in which fuel and air are admitted and combustion occurs.
- Piston, which receives high pressure of expanding hot products of combustion and the piston, is forced to linear motion.
- Connecting rod, crankshaft linkage to convert reciprocating motion into rotary motion of shaft.
- Connected Load, mechanical drive, or electrical generator.
- Suitable valves (ports) for control of flow of fuel, air, exhaust gases, fuel injection, and ignition systems.
- Lubricating system, cooling system.

In an engine-generator set, the generator shaft is coupled to the Engine shaft. The main differences between the gasoline engine and the diesel engine are [4]:

- A gasoline engine intakes a mixture of gas and air, compresses it and ignites the mixture with a spark. A diesel engine takes in just air, compresses it and then injects fuel into the compressed air. The heat of the compressed air lights the fuel spontaneously.
- A gasoline engine compresses at a ratio of 8:1 to 12:1, while a diesel engine compresses at a ratio of 14:1 to as high as 25:1. The higher compression ratio of the diesel engine leads to better efficiency.

Gasoline engines generally use either carburetion, in which the air and fuel is mixed long before the air enters the cylinder, or port fuel injection, in which the fuel is injected just prior to the intake stroke (outside the cylinder). Diesel engines use direct fuel injection to the diesel fuel is injected directly into the cylinder.

The diesel engine is recommended due to their longevity think of an 18 wheeler capable of 1,000,000 miles of operation before major service), lower fuel costs (lower fuel consumption per kilowatt (kW) produced), and lower maintenance costs-no spark system, more rugged and more reliable engine.

Diesel engine power plants are installed where supply of coal and water is not available in desired quantity, power is to be generated in small quantity for emergency services, and standby sets are required for continuity of supply such as in hospital telephone exchange.

To conclude, the main advantages and disadvantages of diesel engines are as below:

- Very simple design also simple installation.
- Limited cooling water requirement.
- Standby losses are less as compared to other power plants.
- Low fuel cost.
- Quickly started and put on load.
- Smaller storage is needed for the fuel.
- Layout of power plant is quite simple.
- There is no problem of ash handling.
- Less supervision required.
- For small capacity, diesel power plant is more efficient as compared to steam power plant.
- They can respond to varying loads without any difficulty.
- High Maintenance and operating cost.
- The plant cost per kW is comparatively more.
- The life of diesel power plant is small due to high maintenance.
- Noise is a serious problem in diesel power plant.
- Diesel power plant cannot be constructed for large scale.

3.4 Transformers

A transformer is a static device consisting of a winding, or two or more coupled windings, with or without a magnetic core, for inducing mutual coupling between circuits. Transformers are exclusively used in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually with changed values of voltage and current. Power transformers are used extensively by traditional electric utility companies, power plants, and industrial plants. After transmission lines, transformers are the most important components of transmission and distribution systems.

The large transformers in power generation stations step up the output voltage of AC generators to higher values for more efficient transmission over transmission lines while also reducing the current values. Somewhat smaller transformers at electrical substations step the transmitted voltage down to the values more useful for regional and local distribution to customers while also stepping up the current.

Transformers can also isolate circuits, suppress harmonics, and regulate line voltage between distribution substations and consumers. Zigzag grounding transformers, for example, derive neutrals for grounding and a fourth wire from a three-phase neutral wire. They can be operated at voltages below their nameplate ratings, but they should not be operated at higher voltages unless they have taps intended for that purpose.

Transformers are classified in many different ways: dry- or liquid-insulated, single-phase or poly-phase, step-up or step-down, and single-winding or multi winding. In addition, they are classified by application. For example, there are voltages or potential transformers (VTs) and current transformers (CTs) that are

used step high voltage and current down to safe levels for the measurement of voltage, current, and power with conventional instruments.

The efficiency of all power transformers is high, but efficiency is highest for large transformers operating at 50–100 % of full load. However, some losses are present in all transformers. They are classified as *copper* or *I2R losses* and *core losses.* Copper losses, also called *load losses,* are proportional to the load being supplied by the transformer. These losses can be calculated for a given load if the resistances of both windings are known. As in generators and motors, the core loss is due to *eddy-current induction loss* and *hysteresis* (molecular friction) *loss,* caused by the changing polarity of the applied AC. Provided that the cores are laminated from low-loss silicon steel, both eddy-current and hysteresis losses will be reduced. Nevertheless, well-designed transformers in all frequency and power ranges typically have efficiencies of 90 % or more.

4 Renewable Energy Resources

Generally, energy resources can be categorized into two groups: long term renewable resources, short-term renewable resources. Nonrenewable energy resources or long term renewable energy resources consist of types of energy whose appearance times are very long and provided that they are consumed gradually, they will be ended. Nonrenewable energy resources consist of all fossil fuel and nuclear fuel energies and the generation techniques based on this kind of energy are discussed previously.

However, short-term renewable energies are continuous and stable energy and can be found in nature as biomass, water energy, wind energy, solar energy, geothermal energy, etc.

As regards the high rate of energy consumption, fossil and nuclear fuels cannot responsible for energy demand of the world autonomously. Moreover, fossil fuels are running out and are rigorously against environment due to their emissions; hence, using of other alternative energy resources such as renewable energy and the development of their application is inevitable.

4.1 Wind Turbines

Wind Turbines are energy converters in which the kinetic energy of wind is converted to mechanical energy. Electricity generation is of several type of application which utilizes the generated mechanical energy.

Wind turbine based power plants have been categorized into two general groups namely; stand alone wind turbine and grid-connected wind turbine power plant

4.1.1 Standalone Wind Turbine Power Plant

Stand alone wind turbine power plants have different kind of applications such as electricity generation in far away points in which very reliable power supply is needed, battery charging, water heating, cooling, etc.

The turbine's rotor diameter of small wind turbine power plant whose main application is battery charging is less than 5 meters and their conventional capacity is between 400 and 1000 W. The heating and cooling application are usually utilized in residential. In this application, wind turbine power plants are directly connected to water heater or an electrical radiator. Moreover, small wind turbine power plants are usually used to generate electricity at far away points as an auxiliary power supply for agricultural affairs.

Standalone wind turbine power plants are usually utilized with batteries and they can be operated with photovoltaic system and diesel generator as a standalone hybrid power system.

4.1.2 Grid-Connected Wind Turbine Power Plant

Grid-connected wind turbine power plant can be classified into single wind turbine and wind farms.

Single wind turbine can be used to supply residential, commercial, industrial, and agricultural loads. The capacity of these turbines is between 10 and 100 kW and installed near the loads. The excess generate electricity may sell to global network and when a wind turbine cannot generate power, the loads should be supplied by energy purchased from network.

Moreover, the increase in capacity of wind turbine faces technical and economical problems; hence, a centralized wind farm with very large number of wind turbines should be used to construct a high capacity wind power plant. Today, wind farms with capacity of more than 100 MW are constructed. The conventional capacity of each wind turbine in a wind farm is between 50 and 500 kW. The amount of generated energy in wind farm depends on the number of wind turbine, the characteristic of each turbine, and wind speed. Furthermore, to prevent turbine's shadow on each other in a wind farm (maximum using of sweep area of all turbines), the turbines are installed with a minimum distance from each other.

4.1.3 Wind Turbine Model

The model of Wind conversion system is well reported in the literatures [5–8]. However, for simplification the wind turbine with doubly fed induction generator consists of three main components: turbine rotor, drive train, and generator. The power extracted from wind by the turbine rotor is given by:

$$P_w = \frac{1}{2}\rho A v^3 c_p(\lambda,\ \beta) \tag{1}$$

where P_w is the power extracted from the wind, ρ is the air density, A is the swept area, v is the wind speed and c_p is the power coefficient which is a function of the tip speed ratio (λ) and the pitch angle of the rotor (β).

The drive train transfers the power from the turbine rotor to the generator. The main modeling equations for the drive train are as below:

$$\frac{d\omega_M}{dt} = \frac{1}{2H_M}(T_M - K.\theta_{MG} - D_M.\omega_M) \tag{2}$$

$$T_M = \frac{P_w}{\omega_M} \tag{3}$$

where T_M is the accelerating torque, K is the effective shaft stiffness, θ_{MG} is the twist in the shaft system, ω_M is the speed of the wind turbine, and $D_M.\omega_M$ is the damping torque in the wind turbine.

A Park model approach is commonly used for the induction generator simulation. The stator is directly connected to the grid and the stator voltage ($\vec{v}_s$) is imposed by the grid. The rotor voltage ($\vec{v}_r$) is controlled by a converter and is used to perform the machine control. This model can be described as follows:

$$\vec{v}_s = R_s.\vec{i}_s + \frac{d}{dt}\vec{\psi}_s \tag{4}$$

$$\vec{v}_r = R_r.\vec{i}_r + \frac{d}{dt}\vec{\psi}_r - j\omega_r\vec{\psi}_r \tag{5}$$

where $\vec{i}$ is the current space vector, $\vec{\psi}_s$, $\vec{\psi}_r$ are the stator and rotor impedance, and R_s, R_r are the rotor and stator resistance.

4.1.4 Wind Turbines

The general categorization of wind turbines is based on the axis direction of turbine. The axis direction of wind turbines can be horizontal or vertical. Horizontal turbines are categorized based on the number of blades into three general categories of two-bladed, three-bladed, and multibladed. In a horizontal wind turbine, the more the wind speed is led to the less the number of blades. Moreover, the axis of vertical turbine is perpendicular to direction of wind. Most of vertical turbine has two blades and the most conventional types of vertical turbine are Darrieus Turbine, Evans Turbine, and Savonius Turbine. The blades of Darrieus turbine are made of aluminum and are in the form of curve-like blade while the Savonius turbines have hemispherical blades. In vertical turbines generator can be installed on earth which is led to simplification of maintenance and service. Figure 4 shows Darrieus, Evans, and Savonius turbines.

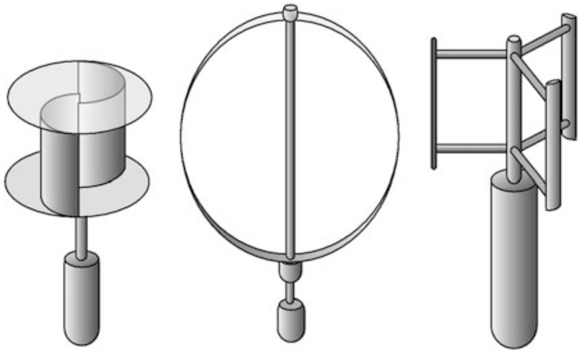


Fig. 4 The schematic of Savonius (*left*), Darrieus (*center*), and Evans (*right*) turbine

4.2 Photovoltaic Systems

PV panels turn sunlight directly into electricity, thanks to a property of their major component—silicon, the most abundant element on earth. Metals conduct electricity if the outer electrons on each atom are attached to the atom so lightly that they can drift away under the influence of a magnetic field. This electron drift is the electric current. Silicon atoms hold on to the electrons that surround them, but some are held less tightly than others and the right-sized hit of energy can knock them loose. Sunlight provides that energy hit, so when light shines on it some electrons are freed. Once the electrons are freed they can flow around a circuit—and that is an electric current. It is important to say that it is the *light*, not the *heat*, from the sun that enables the electricity to flow, so photovoltaics are just as effective in cold countries as in hot—provided there are long hours of sunlight.

4.2.1 Cell, Module, and Array

A solar cell is a semiconductor diode that when stimulated with light, produces an electron and a positive charge on opposite sides of the cell. Wires collect the charge off each side of the cell and take this electricity to the load circuit, such as a light bulb. Wiring cells in series increases the voltage, and in parallel increases the current output. Typically, it is a few square inches in size and produces about 1 W of power. To obtain high power, numerous such cells are connected in series and parallel circuits on a panel (module) area of several square feet. The solar array or panel is defined as a group of several modules electrically connected in a series–parallel combination to generate the required current and voltage.

Mounting of the modules can be in various configurations. In roof mounting, the modules are in a form that can be laid directly on the roof. In the newly developed amorphous silicon technology, the PV sheets are made in shingles that can replace the traditional roof shingles on a one-to-one basis, providing better economy in regard to building material and labor [9].

4.2.2 Types of Solar Cell

There are two ordinary types of solar cell panel [10]:

- Crystalline silicon solar cells have a solid silicon wafer as the semiconductor. The cells are sandwiched between tempered glass and a backing of tough ethylene vinyl acetate (EVA). These cells are protected from moisture. They need to remain cool as their output efficiency can drop by about 0.5 % for every degree Celsius above a standard test temperature of 25 °C. They typically incorporate a gap of approximately 150 mm behind the panels to allow for cooling.
- Amorphous silicon thin film solar cells have silicon in a thin film as the semiconductor. The silicon thin film is deposited on a low-cost substrate such as glass or a thin metal foil. The coating on top may be a flexible material (as opposed to glass), and they may use a flexible mounting system. This type of cell is generally cheaper. They are being developed for integration with materials so they can be part of the building fabric.

4.2.3 Application of Photovoltaic Cells

Some common applications of photovoltaic cells are listed below:

- Highway call boxes.
- Coast Guard buoys and navigation.
- Mountain top radio transmitting and repeating stations.
- Off-grid (rural) homes.
- Grid-tied homes.
- Utility interconnected for Demand Side Management (DSM).
- Utility grid support and bulk power generation.
- Railroad signaling.
- Satellites and space stations.
- Outdoor lighting.
- Calculators and watches.
- Telecommunications, mountaintop relay stations.
- Cathodic protection for metal exposed to the weather and earth.

4.2.4 Photovoltaic Cell Model

The simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell.

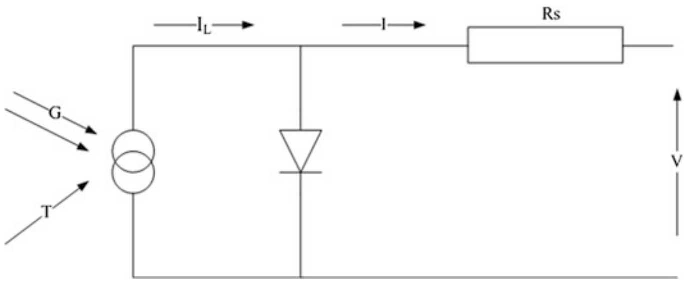


Fig. 5 A simple model of photovoltaic cell

The diode determines the I–V characteristics of the cell. Increasing sophistication, accuracy, and complexity can be introduced to the model by adding in turn.

The model includes temperature dependence of the photo-current I_L and the saturation current of the diode I_0. A series resistance R_S is also included, but not a shunt resistance. A single shunt diode is used with the diode quality factor set to achieve the best curve match [10]. The circuit diagram for the solar cell is shown in Fig. 5.

The equations which describe the I–V characteristics of the cell are

$$I_{PV} = I_{SC} - I_0(e^{q(V+IR_s)/AKT} - 1) \tag{6}$$

$$I_{sc} = I_{sc(T_1)}(1 + K_0(T - T_1)) \tag{7}$$

$$I_{sc(T_1)} = G \times I_{sc(T_1\text{norm})}/G_{(\text{norm})} \tag{8}$$

$$I_0 = I_{0(T_1)} \times \left(\frac{T}{T_1}\right)^{3/A} \times e^{-qV_g/Ak\left(\frac{1}{T}-\frac{1}{T_1}\right)} \tag{9}$$

$$I_{0(T_1)} = I_{SC(T_1)}/(e^{qV_{OC(T_1)}/AkT_1} - 1) \tag{10}$$

$$R_s = -\left.\frac{dV}{dI}\right|_{V_{OC}} - \frac{1}{X_V} \tag{11}$$

where $X_V = I_{0(T_1)} \times \frac{q}{AKT_1} \times e^{qV_{OC(T_1)}/AKT_1}$; q is the electron charge; A is curve fitting constant; K is Boltzmann constant, T is temperature on absolute scale [10].

All of the constants in these equations can be determined by examining the manufacturer ratings of the PV array, and then the published or measured I–V curves of the array.

4.3 Geothermal Power Plant

Geothermal energy is of renewable energies and comes from the extractable heat due to heat of molten masses and decay of radioactive material existed in deep earth. Unlike other energy resources such as wind, solar, tidal, etc., this resource

is continuously available. It means that it can be possible to generate electricity and thermal energy from geothermal resource in every hours of the day, while the other type of renewable resources are available seasonal or under special conditions.

4.3.1 Geothermal Resources

The geothermal resources can be classified as four main groups namely:

- *Hydrothermal*: The hot waters or steams which store in low-deep portion of earth (100–4500 m) is called hydrothermal resources. The hydrothermal resources which can generate electricity should have temperature between 90 and 350 °C; However, it is estimated that two third of hydrothermal resources have temperature between 150 and 200 °C. The richest type of hydrothermal resources contains dry steam or steam with low level of liquid. However, the number of dry steam hydrothermal resources is very few due to the special condition to be existed to form these resources.
- *Under high pressure layers*: These resources are hot springs containing methane which store in the deep of 3000–6000 m under high pressure in sedimentary layer. The temperature of these layers are estimated between 90 and 200 °C.
- *Hot dry rock*: The main idea of electricity generation using hot dry rock is to construct an artificial geothermal spring. To construct this spring, at first, two wells are drilled into hot rocks with 4000–5000 m deep. Then some cracks are made in rocks using nuclear explosion or hydraulic pressure; consequently, two wells are connected via the cracks. The cold water is injected to one well and hot water or hot steam is extracted from the other well. The Hot steam boils a secondary fluid with lower boiling point and finally, the electricity is generated by conducting the hot steam of secondary fluid to turbine. Nevertheless, the main problem of this type of electricity generation is that water does not circulate in a close loop circuit. Since the huge part of injected water penetrates into deep cracks.
- *Magma conduits*: Magmas have the temperature between 700 and 1200 °C, and they contain huge thermal energy. This resource is available in deep of 3000–10000 m; hence, operation of this resource is very difficult

Regardless of economical issues although these resources have different physical characteristics, all of these resources have the ability of electricity generation. Among all these resources, due to the competitive cost, hydrothermal energy is extended up to commercial generation much more than the other types while, the other resources are in the experiment stage. However, hot dry rocks resources have successfully passed the experimental stage and it can be possible to extract energy from these resources [1].

4.3.2 Types of Geothermal Power Plants

Geothermal resources can also be used for power generation. There are four methods to generate power from geothermal energy each can be described as:

- *Dry steam power generation*: In this type of power plant, hydrothermal resources are used to generate electricity. Hence, these power plants can be installed in fields in which there is the capability of dry steam extraction. The dry steam comes out using its natural pressure, then it is passed through a solid particle absorption filter and finally it is directly fed to turbine. The outflow steam of turbine enters a condenser and it loses its heat and is condensed; hence, a vacuum is created between turbine and condenser and consequently, the rotary force and efficiency of turbine is enhanced. The capacity of these power plants is considered about 15–20 MW.
- *Flash-steam power generation*: These power plants are used to utilize the sufficiently hot (more than 160 °C) liquid-dominated reservoirs and generally are categorized into two systems: one-stage and two-stage. In one-stage system, the geothermal hot water existing under high pressure flows over the well due to its very high temperature and pressure and is conducted into flash separator. Due to decrease of pressure, hot waters turn into steam and they are fed into turbine after passing special filter. In two-stage system, after steam generation in first separator, the hot water enters the second separator which have lower pressure. The generated steam of first and second separator flow to high and low-pressure turbine, respectively. The common capacity of these power plants is between 10 and 55 MW.
- *Binary cycle power generation*: These power plants are used to utilize the energy of liquid-dominated hydrothermal reservoirs whose temperature is not very high. The hot water whose temperature is about 65–200 °C is transferred to heat exchanger using pumps or its natural temperature. Then, the hot water transfers its heat to second fluid such as Isobutene or Freon whose boiling temperature is low. The steam generated by second fluid plays the role of working fluid of plant.
- *Combined/hybrid power generation*: In these power plants in addition to geothermal energy, other types of energy (such as fossil fuels) may be used to heat the working fluid. The geothermal fluid exchanges its heat with working fluid (pure water) in a heat exchanger leading to preheat of working fluid. The hot water is turned to steam in a steam generator using combustion of conventional fuels.
- *Power generation with Rotational Separation Turbine (RST)*: In these power plants, the geothermal hot water goes into the separator and parts of it turn into high pressure steam which can be fed into high pressure turbine. The remaining fluid in separator is conducted to RST which is coax with steam turbine. The

RST system has two advantages: not only does kinetic energy of RST help rotary power of steam turbine but also some low-pressure steam is generated in RTS which can be conducted to low-pressure turbine and enhance rotary power of steam turbine [11].

4.4 Biomass Power Plants

Generally, biomass resources refer to materials which are made up from planets and organisms. Unlike fossil fuels which are found in the centralized layers in the world, biomass resources are available in decentralized form. Biomass resources which are suitable for energy generation are namely as: wood fuels, agricultural waste, energetic shaw with short circulation period, herbal products such as sugarcane, herbals containing vegetable oil, herbals containing hydrocarbon, industrial and rural waste, etc.

Moreover, three technologies can be utilized to convert biomass energy. These technologies are known as: Direct combustion process, Thermochemical process, Biochemical process, each of which uses gasification reactors of type: fixed bed reactor and fluidized bed reactor [12].

Direct combustion process is the simplest technology to convert biomass energy. However, biomass material in this technology has low thermal energy contents; hence, the efficiency of this technology is less than efficiency of fossil fuel combustion. To enhance the thermal efficiency of biomass, the raw materials are processed using thermochemical process and different types of biofuels such as wood coal (at temperature less than 400 °C), ethanol, and methane (at temperature more than 1000 °C) are produced. The produced materials have more energy contents than biomass raw materials. However, in the biochemical process biomass material converts to biofuel using metabolic microbial organisms' actions. This process utilizes anaerobic fermentation to generate biofuel and biogas.

Several types of power plants are available to convert biomass energy to electricity. In big power plants, biomass is used as co-firing fuel; however, in small power plants biomass can be used as single fuel of plant. Plants with combustion engines, thermal biomass power plant, gas biomass power plant, combined cycle biomass power plants are the most commercial biomass which are used to electricity generation [13].

In power plants with combustion engines, different types of biofuel produced by biomass can be substituted with conventional fuel of combustion engines. However, in other types of power plants, biomass is used as the fuel of boiler furnace in thermal biomass or the fuel of combustion room of gas biomass power plant. Figure 6 illustrates a biomass combined cycle power plant.

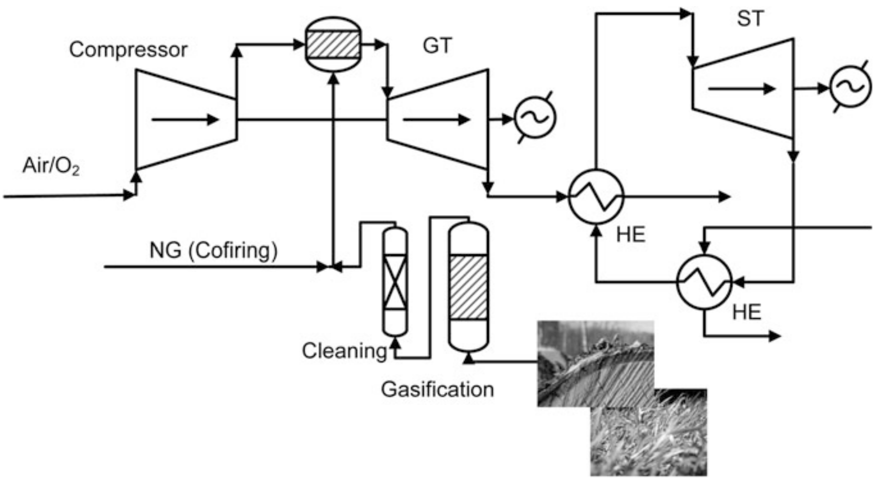


Fig. 6 Flow diagram of a combined cycle power plant using biomass as main fuel

4.5 Tidal Power Plants

The common technologies of tidal power plants are relatively full-fledged. Yet, the common methods to extract tidal energy require more economical performance. Generally, to generate electricity from tidal energy two different methods are suggested. First method needs to construct dam and water storage reservoir while in the second method tidal currents are used; hence, there is no need to dam construction.

Tidal power plants which need dam construction are categorized based on their reservoir combination. The categorization includes: a reservoir for ebb, a reservoir for flood, a two-way reservoir for ebb and flood, two reservoirs for ebb and flood, and two high and short reservoirs with one-way system [10, 14].

A reservoir for ebb: In this system, the water flows to reservoir via turbine in ebb situation and generator which is coupled with turbine generates electricity while the floodgates are opened in flood situation; consequently, the reservoir is evacuated.

A reservoir for flood: In this system, when floodgates are opened, at first, water storage reservoir will be fully filled. Then, if water level of reservoir is higher than water level of sea in flood situation the water of reservoir will be evacuated to sea via turbine and finally the generator which is coupled with turbine generates electricity.

A two-way reservoir for ebb and flood: In this system, a two-way single reservoir is used. However, comparing with other single reservoir, this scheme needs also a two-way turbine to generate electricity in both ebb and flood situations. Using this system, the pause time of electricity generation between ebb and flood

situation is significantly reduced. Hence, more electricity can be generated comparing single reservoir schemes; however, generated energy still has fluctuations.

Two reservoirs for ebb and flood: The procedure of electricity generation in this system is that water flows from sea to one reservoir in the ebb situation and flows from another reservoir to sea in flood situation. Comparing with single reservoir systems previously described, the generated electricity is more continuously in this system; however, they need complicated scheme to generate energy.

Two high and low reservoirs with one-way system: In this system, two reservoirs are constructed in such way that one has a dam with high height while the other has a dam with low height. The turbine is placed in the wall between two reservoirs and spins with water flow from higher reservoir to lower reservoir; hence, the electricity is generated in generator which is coupled with turbine. Comparing to previous systems, the construction of the wall between two reservoirs is led to increasing in cost of constructions significantly. The mechanism of this system is that the higher reservoir is fully filled in the ebb situation by opening of floodgates of higher reservoir. When the water level of the sea decreases during flood situation, to prevent water flow from reservoir, the floodgates are closed. By continuously flowing of water from high reservoir to low reservoir via through turbine the electricity is generated. When the level of water in sea is less than the level of water in lower reservoir, the floodgates of lower reservoir will be opened to flow water to sea. This process continues until the water level of the sea equals to water level of lower reservoir. Then, the floodgates of this reservoir are closed to prevent flowing of water from sea to reservoir. Then lower reservoir is filled by higher reservoir through turbine. Finally to complete the loop, when the water level of sea is more than water level of higher reservoir, its floodgates will be opened and filled. Although the generation of electricity through this method is continuous, it has still fluctuations.

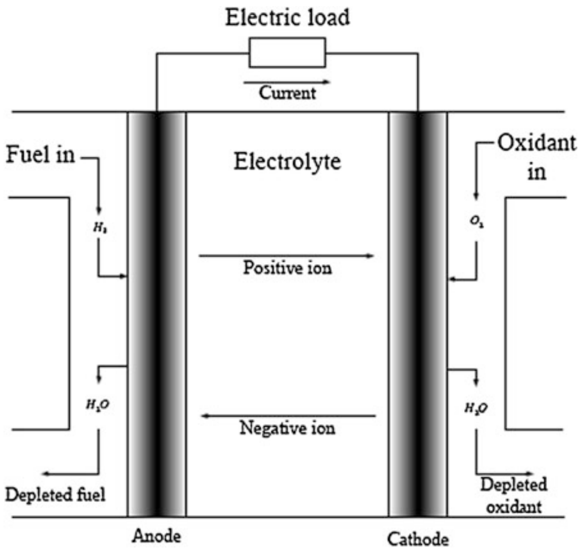
Tidal current power plants: These power plants are taken into consideration in recent years significantly due to no need for dam construction and high height tide and environmental issues. The power of tidal current power plants can be calculated as below:

$$P = 0.5\frac{M}{t}v^2 = 0.5\frac{\rho V}{t}v^2 = 0.5\rho Q v^2 = 0.5\rho A v^3 \tag{12}$$

where ρ is water density (=1000 kg/m^3), Q is flow rate of tidal current (m^3/s), v is the speed of tidal current (m/s), M is the mass of flowing water (kg), A is the cross section of flowing water (m^2), and V is the volume of water (m^3).

As can be seen from Eq. (12), the most important condition for electricity generation of a tidal current power plant is tidal current with sufficient speed. Although the construction of these power plants eliminates the cost of dam construction, comparing with the other types which need dam, the power density of this method is very low.

Fig. 7 Simple schematic diagram of fuel cell [17]



4.6 Fuel Cell Power Plant

A fuel cell is an electrochemical device that oxidizes fuel without combustion to directly convert the chemical energy of the fuel cell into electrical energy [15]. In simple terms, the fuel cell produces electric power by feeding a hydrogen-reach gaseous fuel to porous anode as an oxidant (air) is supplied to the cathode. The electrochemical reactions taking place at the electrodes result in electric current injected to the external circuit. Figure 7 schematically shows a simplified diagram of a fuel cell. In a fuel cell powered by hydrogen, the reverse reaction of water electrolysis takes place [16, 17]:

$$H_2 + 0.5O_2 \rightarrow H_2O \tag{13}$$

Except in Molten Carbonate Fuel Cell in which the general reaction is:

$$H_2O + CO_2 \rightarrow H_2 + CO_2 + 0.5O_2 \tag{14}$$

The chemical energy content of hydrogen is directly converted to electrical energy in the fuel cell. Therefore, a fuel cell can theoretically obtain higher electrical efficiency than thermal engines that are limited by the efficiency of the Carnot-cycle. However, kinetic over-voltages at the electrodes and electrical resistance cause relatively high losses in practical systems. Although several types of Fuel Cell technology are available, mostly important types of fuel cell technologies are [16]:

- Phosphoric Acid Fuel Cell (PAFC).
- Proton Exchange Membrane Fuel Cell (PEMFC).

- Alkaline Fuel Cells (AFC).
- Solid Oxide Fuel Cell (SOFC).
- Molten Carbonate Fuel Cell (MCFC).

PAFCs are currently being considered for use in heavy duty vehicles. Their major problem for use in vehicular application is their slow startup (since the cell has to be heated to over 200 °C), high costs, and excessive weight. Since PAFCs work best at a constant output, their application will be better in hybrid systems where a battery or other device meets the high-power demands of acceleration.

The basic components of a phosphoric acid fuel cell (PAFC) are the electrodes consisting of finely dispersed Pt catalyst on carbon paper, Sic matrix holding the phosphoric acid and a bipolar graphite plate with flow channels for fuel and oxidant. The operating temperature ranges between 35 and 200 °C and it can use either hydrogen or hydrogen produced from hydrocarbons (natural gas) or alcohols as the anodic reactant. In the case of hydrogen produced from a reformer with air as the anodic reactant, a temperature of 200 °C and a pressure of 8 atm are required for better performance. The heat generated by FC can be utilized in endothermic reaction of fuel process in fuel reformer or it can be used as heat supply to generate heat water. PAFCs are advantageous from a thermal management point of view. The rejection of waste heat and product water is very efficient in this system and the waste heat at 200 °C can be used efficiently for the endothermic steam reforming reaction. The system is extremely sensitive to CO and H_2S which are commonly present in the reformed fuels. A major challenge for using reformed fuel, therefore, lies in the removal of CO to a level of less than 200–300 ppm. CO tolerance is better at temperatures more than 180 °C. Removal of sulfur is still essential.

PEM fuel cells, also called solid polymer electrolyte fuel cells (SP(E)FC) use a proton (hydrogen ion) conducting membrane which stays sandwiched between two platinum-catalyzed porous electrodes728. Initially, these membranes were based on polystyrene, but at present a Teflon-based product "Nafion" is used. This offers high stability, high oxygen solubility, and high mechanical strength. The cell operating temperature is quite low (60–120 °C) and operating pressures can be in the range of 1–8 atmospheres. The fuel cell requires humidified hydrogen and oxygen for its operation. The pressures, in general, are maintained equal on either side of the membrane. Operation at high pressure is necessary to attain high-power densities, particularly when air is chosen as the anodic reactant. The major contaminant of the PEMFC system is carbon monoxide. Even a trace amount of CO drastically reduces the performance level. It is best to use a fuel which is virtually free of CO for PEMFC. On the other hand, it is tolerant toward CO_2 contamination [18].

AFCs offer high-power density and cold-start capabilities. Alkaline fuel cell represents the oldest and most widely used fuel cell systems in the U.S. space program and have gone onboard most of the manned space missions. AFCs use potassium hydroxide as the electrolyte and hydroxyl ions are the conducting species. Because of the alkaline electrolyte, no noble metal catalyst is required.

AFCs operate at 60–250 °C which is relatively low compared to other fuel cells. Operating pressure is normally atmospheric pressure. From a system point of

view, removal of product water and heat is difficult at these low temperatures. In space shuttles, closed-loop hydrogen circulation as well as dielectric liquid circulation is used for heat management. Some of the terrestrial fuel cells are process air-cooled. Alkaline fuel cell can operate only with pure H_2 and pure O_2 Even a small level (less than 250 ppm) of CO_2 is sufficient: to carbonate the electrolyte and can spoil the electrode. Several processes for cleaning of the electrode after contamination are available (Physical adsorption-Selexol process, Fluor solvent process, pressure swing adsorption) but each is expensive and none are totally effective [18].

Solid oxide fuel cells (SOFCs) are solid-state power systems and at present use yttrium-stabilized zirconium as the electrolyte. The operating temperature is high, typically 1000 °C. SOFCs can be used as co-generators to supply both electricity and high quality waste heat. In this cell, a conversion efficiency of more than 50 % can easily be attained. Because of high temperature, the SOFCs can handle impurities in the incoming fuel better. SOFCs can operate equally well on dry or humidified hydrogen or carbon monoxide fuel or on mixture. The main poisoning factor for SOFC is H_2S. Though the sulfur tolerance level is approximately two orders of magnitude greater than other fuel cells, the level is below 80 ppm [19].

In the molten carbonate fuel cell, a molten alkali carbonate mixture, retained in a porous lithium aluminate matrix, is used as the electrolyte. The conducting species is carbonate ions. The operating temperature is in the range of 600–800 °C, high enough to produce suitable qualities of waste heat. This waste heat can be used for fuel processing and cogeneration, a bottoming cycle, or internal reforming of methane. MCFCs normally have 75 % fuel (hydrogen) utilization. The advanced form of MCFC referred to as internal reforming molten carbonate fuel cell (IRMCFC) may consume lower hydrocarbons (CH,) directlyi6. It is intrinsically efficient since the heat produced at the anode is used for reformation of hydrocarbons. Normally their efficiencies are 50 % or higher MCFCs do not suffer from CO poisoning and, in fact, can use CO in the anode gas as the fuel. They are extremely sensitive (1 ppm) to the presence of sulfur in the reformed fuel or oxidant gas stream. The presence of HCl, HF, HBr, etc., causes corrosion, while trace metals can spoil the electrodes. The presence of particulates of coayfine ash in the reformed fuel can clog the gas passages [15].

Table 1 summarizes the characteristics of different types of Fuel Cells. It should be noted that high rated power can be achieved by recovering of heat generated by FC in other thermal processes such as thermal power plants.

4.7 Storage Systems

Storage system is another component of hybrid power system. Due to the variable nature of wind and photovoltaic systems storage is required to supply demand continuously and reliably. Hence, when the sufficient wind and solar power are available, loads will directly supplied by these resources and the excess power can

Table 1 Characteristics of different types of fuel cell

	AFC	PAFC	MCFC	SOFC	PEMFC
Electrolyte	Potassium	Phosphoric acid	Molten alkali carbonate	Ceramic	Polymer
Operation temperature (°C)	60–250	35–200	600–800	700–1000	60–120
Fuel	Pure processed H_2	Processed H_2	Processed H_2/CO	Processed H_2/CO_2/CH_4	Processed H_2
Oxidant	O_2	O_2/air	CO_2/O_2/air	O_2/air	O_2/air
Electrical efficiency	>50	40–50	50–60	40–60	40–50
Applications	Space Industrial, transportation, military industrial, submarine	Industrial, commercial, transportation, airplane, power plants	Industrial, commercial, airplane, power plants	Industrial, commercial, airplane, power plants	Industrial, commercial, transportation, power plants(up to several kW)
Life time (hours)	>1000	>40000	>40000	>15000	>40000
Rated power (kW)	–	1–20000	50–50000	1–50000	1–3000

be stored in battery. There are three main goals for utilization of storage system in hybrid power system: to supply demand at a constant output, to compensate the instantaneous lack of renewable energies, to operate system as a dispatchable unit.

Different storage systems can be utilized in hybrid power system. The most important technologies are flywheel, compressed air energy storage (CAES), hydrogen production, ultra-capacitor, superconducting magnetic energy storage, thermal reservoir, etc., among whom battery is the most commercial technology to store energy in hybrid power system.

The classification of energy storage system is based on the energy, time, and transient response required for their application [12]. In medium and long term applications, storage system is classified based on energy density requirements and in short and very short-term applications, the classification is based on power density requirement.

In transients (milliseconds), the main features of storage is to compensate voltage sags, to improve harmonic distortion and power quality, to rid through disturbances, etc. In very short term (a few cycle of power frequency), storages cover load during startup, compensate transient response of renewable-based converters, increase system reliability during fault management. The short-term (minutes) capabilities of storages are to cover load during short-term load peak, to decrease needs of startup backup generator, and to improve maintenance needs of fossil fuel-based generators. In medium term (a few hours) they store the excess energy generated by renewable resources. In long term (e.g., several hours), storages provide reduction in fuel consumption and decrease waste of renewable energy, eliminate backup of conventional generators. Storage systems using in planning period are such as pumped hydro and compressed air systems. In this period, it can be possible to store hydrogen from biomass and renewable-based systems.

Figure 8 depicts storage technologies organized in categories of ride-through, power quality, and energy management. Storage systems include lead–acid batteries, advanced batteries, low- and high-energy flywheels, ultra-capacitors, superconducting magnetic energy storage (SMES) systems, heating systems, pumped hydro, geothermal underground, and compressed air energy storage (CAES).

5 Supervisory Control of Hybrid Power System

Supervisory controller is used to define a plant wide control system, and supervision refers to operation overview, planning & scheduling, co-ordination and execution of actions that improve performance, economy and reliability. The dynamic control is not a task of the supervisory controller.

A supervisory controller for hybrid power systems should continuously monitor the operating state of the system and keep it within the specified target domain. The control actions should ensure that the system's operating goals are achieved

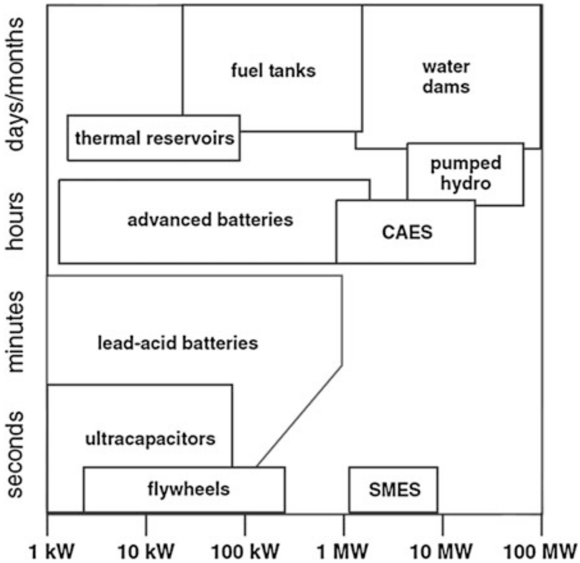


Fig. 8 Categorization of storages technologies based on energy [12]

and maintained in spite of uncertainties and resource constraints. It could also act to prevent safety critical system states or to alleviate consequences of failures in system components.

The primary goal of the supervisory controller is power supply optimization. Two basic tasks are necessary to accomplish this: (1) Improving the performance of the system (for example, increasing fuel savings or reducing generation cost); and (2) keeping the operational parameters (frequency and voltage, load at the diesel engines, etc.) within their limits. The control actions used to perform these tasks are (1) switching on/off components, i.e., changing the system's mode of operation, and (2) changing operation set points of some (controllable) components.

As is shown by Fig. 9, a supervisory control system includes three main parts namely Plant, Interface, and Controller. In this scheme to gain the benefits of discrete controllers, it is possible to design a discrete-event controller system for hybrid power systems. The explicit of identification of interfaces between continuous and discrete dynamics has been one of the characteristics of supervisory control of HPS. Hence, the supervisory controller supervises the operation of system while operation control is distributed between local controllers and regulators. The distributed control allows the system components to use their own control systems. For instance, a wind power generation system has a voltage regulator to control its output voltage and a rectifier-inverter system to maintain its output frequency at power frequency.

The supervisory controller selects the optimal operation mode for the system considering the specific operating goals, the system configuration and constraints. Moreover, the supervisory control can determine set points for different components

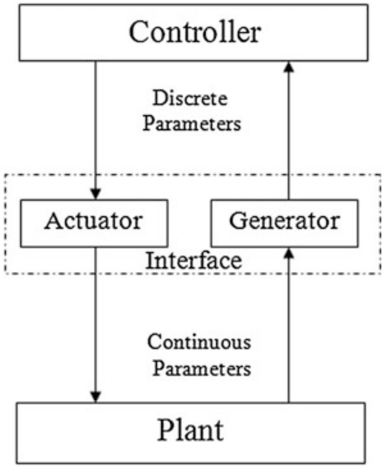


Fig. 9 Supervisory control system

at different modes of operation and send them to their respective local controllers. For wind generators the set points could be the power output value and the output voltage. Figure 10 illustrates a scheme of the supervisory control system [20]. The system consists of two main parts: *hardware* and *software*. The *hardware* is portrayed by the type of computer and its features. The interfaces with the plant which should be controlled (*process interface*) and the operators (*man–machine interface*) are major parts of the hardware and affect the *application programs* (*software*) related to the I/O operations of each interface. The *software* is divided into *operating system* (OS)—for each computer type there are several OS available in the market, and *application programs*, which are the algorithms of the control system. Normally, *development programs* develop offline, the control algorithms.

The aim of supervisory control is to enhance the economics of Hybrid Power Systems by ensuring efficient operation, reliability, and long life time. Furthermore, the controller should be robust enough to remain in operating mode efficiently after failures in components.

The difficulties related to operation of HPS, which are not present in large interconnected grids, are mainly caused by:

- The uncertainty and complication related to generation and conventional generators operation of HPS, respectively
- Lack of knowledge on power quality issues in HPS.

The stochastic nature of the renewable resources causes large variations of power generation. The main goal of HPS control is to supply load demand reliably regardless of generation variations while frequency and voltage maintain within acceptable limits.

Separation of different types of HPS control has a great importance. It should be noted that in order to control HPS dynamically, controllers performed in scales of

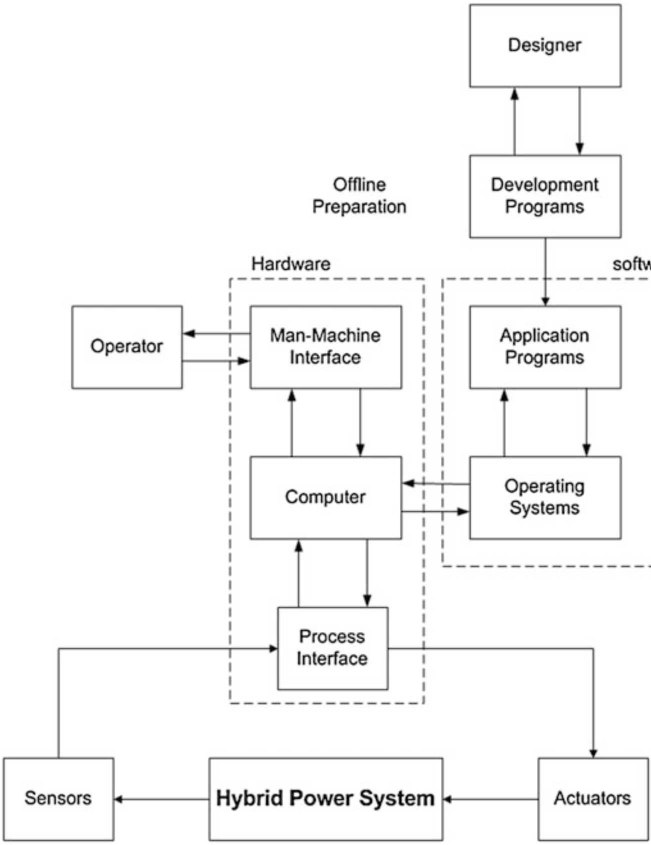


Fig. 10 Schematic of supervisory control problem [20]

seconds or milliseconds have been used. The dynamic control includes frequency and voltage control as well as stability issues and etc. Nevertheless, supervisory control makes decision about optimal operation of HPS including energy flow as well as actions to enhance system operation and the value of power generation of conventional generators. The time scale of operation strategy which is yielded by supervisory controller is about several seconds to hours.

In HPS with high renewable energy penetration, conventional generators whose fuel costs are significant can be switched off when the energy produced by renewable energy generation is sufficiently high to meet the demand. If accurate load and renewable power prediction are achieved, in order to significant enhance of system economically it would be possible to schedule service status of conventional generators.

Another problem to consider with conventional generator operation is that there can be relatively long time intervals necessary to start and stop the units. For

example, a system collapse can happen during a diesel generator startup if the renewable power decreases faster than the startup time interval.

Normally, the procedure adopted by power plant operators is to keep always some conventional power capacity available in order to avoid system collapse in case of a sudden loss of renewable power or increase of load.

Nevertheless, this situation frequently conducts diesel generators to run under loaded and deteriorates the fuel savings.

5.1 Operation Strategies

An operation strategy should help the supervisory controller to make decision about generation, controllable loads, and storages.

The following parameters should be considered in the operation of HPS

- The characteristics of the demand, seasonal variations, peaks and valleys, etc.
- The characteristics of the renewable resources, such as mean values, standard deviations, frequency of occurrence, extreme values, diurnal and seasonal variations, etc.
- The characteristics of the conventional generators, such as specific fuel consumption, limits of operation, etc.
- The configuration of the system, i.e., number and type of components (renewable energy generators, conventional generators, controllable loads, type of storage, etc.).
- Power quality requirements—the required quality of the supply, in terms of variations of frequency and voltage and the probability of loss of load. Therefore, some operation strategies may be more effective in particular applications depending on the system goals and characteristics.

The operation strategies include spinning reserve, load management, minimum run-time of conventional generator, storage management, etc.

5.2 The Control System Architecture

Figure 11 illustrates the architecture of supervisory controller. It is worthwhile to note that the arrows in the Fig. 11 do not show the actual information flow but they depict the control flow of supervisory control process.

The data from sensors and messages from controller are sent to the *input interface*. The operator can be interfaced with control system to supply information, to change parameters, and to choose operation strategies.

The input data is stored in the *data base* module which is common database. The received data is filtered and analyzed in this module and the information in the

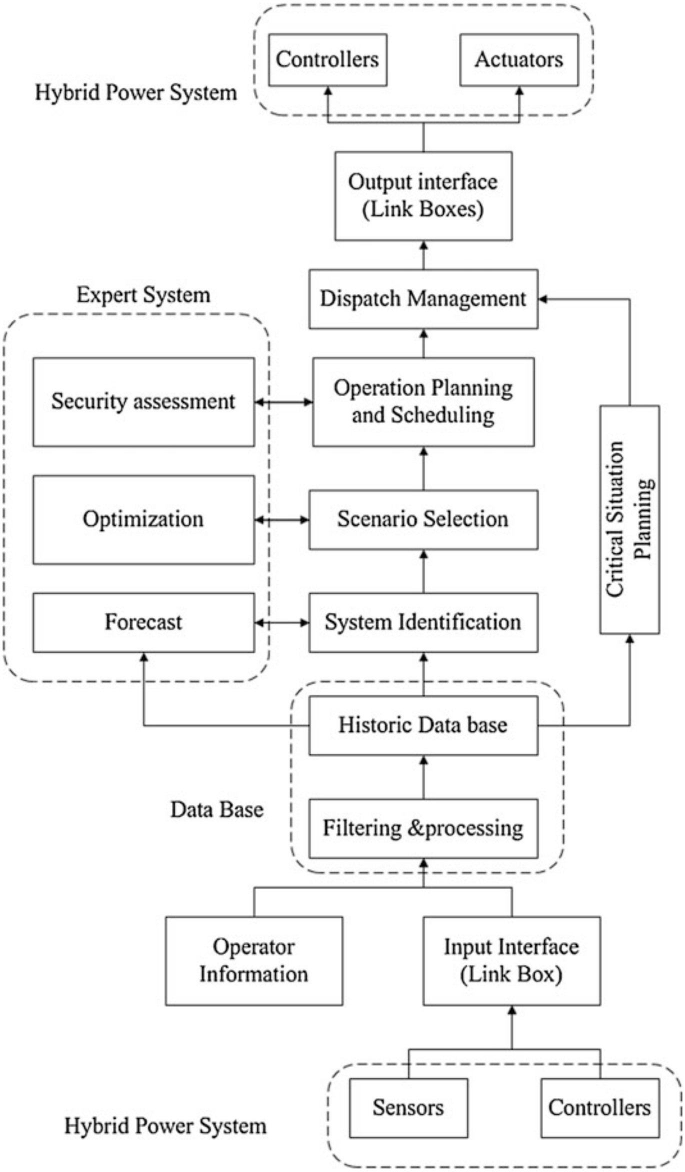


Fig. 11 Control flow of the supervisory controller architecture [20]

database can be accessed by the other parts of controller for further analysis. To run simulation and security assessment of system the information of historic data base are used by other parts of the system.

As far as dynamic control of power system is not a task of supervisory controller, the calculations, and information of abnormal situation are not included in database information.

Identification of current status of system based on values of state variables is interpreted by *system identification* module. The input of this module is the information of *data base* module. This information consists of grid parameters and operating status. This module identifies current operating system and predicts short period events of the system.

To optimize system operation via possible actions selection and to compensate changes in system parameters and to keep the operation conditions of conventional generators, *scenario selection* module is used. It should be noted that the list of possible actions are generated depending on the main goal, system configuration, and constraints. This module makes decisions about components' switching on/off and control parameters' changes.

The possible actions are sent to the *operation planning and scheduling* module and a plan for selected action is established. The planed action is executed in the *dispatch management* module. This module connects with interface of all components via *output interface* module. This module translates the commands and messages and sends signals and commands to actuators and controllers.

The *critical situations planning* module contains predefined rules and actions to compensate large disturbances in the system. It bypasses the basic decision model when safety critical system states are identified. This allows the supervisory controller to act very fast in case of emergency (or serious alarm) in order to protect the system.

The *expert systems* module comprises three distinct tasks: forecast, optimization, and security assessment. These expert systems are used to improve efficiency of the control algorithm. Several methods for forecast, optimization, and security assessment can be implemented and the structure of the program allows the user to select the algorithms (methods) to be included in the control system.

6 Hybrid Power System Modeling, Control, and Management

Hybrid power system (HPS) is any autonomous electricity generating system combining renewable energy sources and conventional generators. Wind-diesel, Fuel cell- Wind, Photovoltaic-Wind-Fuel cell systems, etc. are a subclass of HPS. The purpose of these systems is to supply reliable energy whose power quality is acceptable while the penetration of renewable resources is as much as possible. Furthermore, the lower generation costs due to low cost of fuel and the advantages of fuel saving should balance the high investment costs for renewable energy generators, controllers, dump loads, storage units, converters, etc.

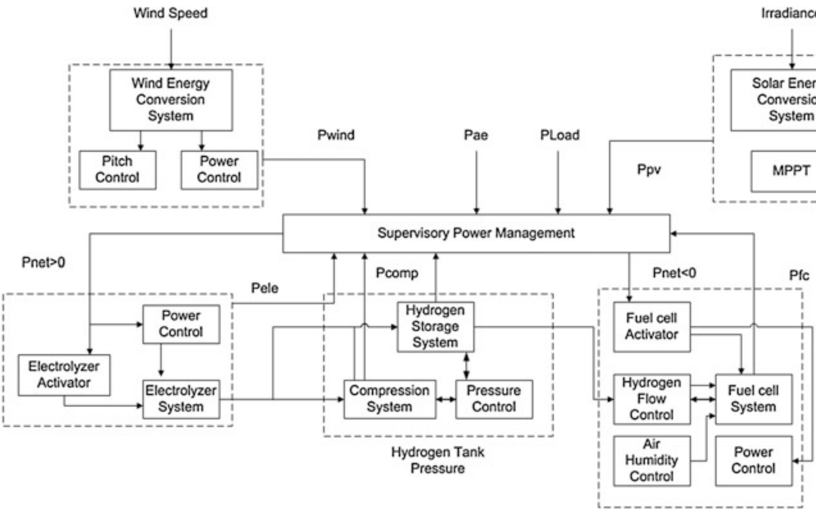


Fig. 12 Block diagram of management and control of a hybrid power system consisting of wind turbine, photovoltaic cell, fuel cell, storage system, and electrolyzer

The control system of Hybrid Power System consists of a supervisory controller for the overall power management, and secondary low-level controllers, which manage various parameters for the individual components.

The power flow in the hybrid system is shown in Fig. 12. The converted energy from the renewable sources can be either used directly to meet the load demand, or transferred to the hydrogen production process.

The logic of the decision process is based on Eq. (15) [21]:

$$P_{\text{net}} = (P_{\text{wind}} + P_{pv}) - (P_{\text{load}} + P_{ae}) \tag{15}$$

where P_{load} is the load demand and P_{ae} is the power consumed by auxiliary equipment including compressors, controllers, and safety equipment.

At each sampling interval, if the excess wind and Photovoltaic (PV) generated power is greater than the rated power of the electrolyzer ($P_{\text{net}} < P_{\text{ele}}$), the electrolyzer stack is activated to generate hydrogen, which is then delivered to the hydrogen storage tanks through the compressor unit. On the other hand, when there is a deficit in power generation ($P_{\text{net}} < 0$), the Fuel Cell (FC) is activated to consume the stored hydrogen and convert it to electricity. The fuel cell activation will occur if there is sufficient hydrogen in the storage tank. Otherwise, the hybrid system enters the “hydrogen storage” mode. This can occur as a consequence of either extreme operational conditions, such as low availability of renewable energy and very high load demand, or inappropriate unit sizing. An additional problem is operating the electrolyzer and fuel cell at their full capacities, i.e., without any local control. The amount of power required to run the electrolyzer depends on its capacity, and if it is operated at the rated capacity, at some point even if $P_{\text{net}} > 0$,

the amount of power consumed by the electrolysis process would overcome the power generated by the RE sources. The solution to this problem is implementation of local controllers on the electrolyzer and fuel cell. Their primary objective is to ensure using the suitable extent of the electrolyzer and fuel cell's capacity in order to use the excess energy and stored hydrogen in the most efficient way. The local, or low level, controllers ensure maximum energy extraction of the RE side of the hybrid system, as well as proper hydrogen generation and utilization.

Despite all improvements, PV modules still have relatively low conversion efficiency. *V–I* and *V–P* characteristic curves for a PV array specify a unique operating point at which the maximum possible power is delivered. The Maximum Power Point Tracking (MPPT) algorithm is used for extracting the maximum available power from the PV module under certain voltage and current conditions. There are several MPPT techniques reported in the literature. The perturbation and observation method (P&O) is one of the common and effective ways of power tracking for PV arrays. The MPP tracker operates by periodically incrementing or decrementing the solar array current. If a given perturbation leads to an increase (decrease) of the output power of the PV, then the subsequent perturbation is generated in the same (opposite) direction.

The wind turbine power output varies with the wind speed. The control objective is dependent on the wind velocity range. Above the cut-in wind speed, the control system extracts maximum power according to the turbine specific maxima power trend. The control action is based on the difference between the actual turbine speed (ω_r) and the corresponding maxima power. This offset is sent to two PID controllers to adjust the current and voltage of the rotor converter in order to obtain the maximum power. Between the rated and cutout speed, the pitch angle controller takes action. In this velocity range, the turbine speed (ω_r) is compared to the desired turbine speed and the offset is sent to the pitch controller to manipulate the pitch angle and keep the output power constant. The pitch angle operational range and its rate of change are the constraints applied on this controller. In the case of wind speed higher than the cutout speed, the system is taken out of the operation for the protection of its components.

As previously mentioned, the electrolyzer and fuel cell are commonly operated at their maximum capacity and this can drastically decrease the overall efficiency of the system. In this study, separate model predictive controllers are designed and applied to control the electrolyzer and fuel cell performance.

For control design purposes, the nonlinear models of the electrolyzer and fuel cell were linearized around selected operating points to obtain a state space model in the following form:

$$\begin{cases} \dot{x} = Ax + Bu + B'w \\ y = Cx \end{cases} \tag{16}$$

where x, u, w and y are the model states, manipulated variables, disturbances, and model outputs, respectively.

These variables for the electrolyzer are [21]

$$\begin{cases} x_{ele} = \left[\delta N_{O_2,a}, \delta N_{H_2O,a}, \delta N_{H_2,c}, \delta N_{H_2O,c}\right]^T \\ y_{ele} = [\delta P_{ele}, \delta V_{ele}, \delta N_{H_2}, \delta p_{H_2}]^T \\ u_{ele} = [\delta I_{ele}] \\ w_{ele} = [\delta p_{ele}] \end{cases} \tag{17}$$

where the operator δ indicates the deviation from the operating point, I_{ele} is the electrolyzer's current, P_{ele} is the electrolyzer's consumed power, V_{ele} is the electrolyzer voltage, p_{ele} is the electrolyzer's operation pressure. P_{ele} is considered as the controlled variable and other outputs are measured outputs. The other parameters have been introduced in the electrolyzer modeling section.

The fuel cell state space model variables are:

$$\begin{cases} x_{fc} = \left[\delta p_{fc}, \delta N_{O_2,\,c}, \delta N_{H_2O,\,a}, \delta N_{H_2,\,a}, \delta N_{N_2,\,c}\right]^T \\ y_{fc} = \left[\delta P_{fc}, \delta V_{fc}\right]^T \\ u_{fc} = \left[\delta I_{fc}\right] \end{cases} \tag{18}$$

where P_{fc} is the fuel cell generated power, chosen as the controlled variable, and V_{fc} is fuel cell voltage, considered as the measured output.

For both systems, the control objective is to keep the power (P_{ele} and P_{fc}) at desired set points which are imposed by the P_{net} value from the power management controller. Constraints on upper and lower limits as well as the rate of change for power were implemented to avoid large and nonrealistic variations.

The model predictive controller is designed to minimize the following finite control and horizon performance index [21]:

$$\min \sum_{i=1}^{n_y} \left|\alpha\left[y_i - y_{i,ref}\right]\right|^2 + \sum_{i=1}^{n_u} |\beta[\delta u_i]|^2$$
$$s.t. \begin{cases} y_{lb} \le y \le y_{ub} \\ \delta y_{lb} \le \delta y \le \delta y \\ u_{lb} \le u \le u_{ub} \end{cases} \tag{19}$$

where α and β are input and output weight factors and n_y and n_u are the prediction and control horizons. The objective function was subjected to the set of constraints, the fuel cell and electrolyzer's operational limitations (y_{ub}, y_{lb}, u_{ub}, u_{lb}) and the rate of change in the electrolyzer and fuel cell power. Aside from power control, two PI controllers were implemented to minimize the pressure difference between the cathode and anode by manipulating the hydrogen flow, and keep the desired air humidity by injecting appropriate amount of water vapor into the air stream entering the cathode side of the fuel cell.

7 Conclusion

Hybrid power system is electricity generation system combining both renewable and conventional electricity generation beside energy storages. This power system may use any renewable energy resources such as wind, solar, water, geothermal, and biomass. These kinds of energies may either convert to hydrogen to store in energy storage system or generate electricity in fuel cells. To manage the wide range of energy resources and energy generation system, a control and management system is inevitable; hence, a supervisory control system is used to manage and control energy generation system.

In this Chapter, an overview of hybrid power system was presented. First, conventional fossil based power plants such as steam, gas, combined cycle, and nuclear and relevant generators such as AC and DC generators were introduced. Then, renewable-based power plants such as wind, solar, geothermal, tidal, hydro, and biomass power plant were introduced. Moreover, different kind of fuel cell as non-fossil based energy generation system and their generation mechanism was presented. Storage devices are other components of hybrid power system whose types were described in this chapter briefly. Any possible combination of these resources may be used in a hybrid power system. Finally, supervisory control and management system and its relevant operation strategies were described.

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